

CONCEPT VALIDATION AND DETECTABILITY LIMITATIONS FOR DIRECT-SEQUENCE SPREAD-SPECTRUM ULTRASONIC EVALUATION SYSTEM

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INTRODUCTION

Direct-Sequence Spread-Spectrum Ultrasonic Evaluation (DSSSUE) technology has now taken a practical shape [1]. Two independent prototype instruments have been designed with different approaches, a hardware and a software implementation. The instruments record the aggregate acoustic state of the test object and the associated measurement system in the form of "ultrasonic correlation signature" [1,2]. These correlation signatures are compared with the signatures obtained at a later point in time (or from an identical object) to detect if the test object has undergone any change in its geometry, composition and homogeneity etc. The DSSSUE instruments have been undergoing concept validation and detectability verification for the ultrasonic testing of both large structures and small piece parts. This paper reports on the results of these tests, the detectability limitations that apply to practical scenarios are described, including limitations due to processing time, sampling granularity, and transducer placement. Various tradeoffs associated with implementation of the DSSSUE technique are addressed.

THEORY

Figure 1 shows the basic signal processing model of the DSSSUE system [2]. The governing equation for the output cross-correlation, $R_{sr}(\tau)$, can be written as [3],

$$R_{sr}(\tau) = h_c(t) * \{s(t-\tau) r(t)\} \quad (1)$$

where $h_c(t)$ is the impulse response of the correlation filter, $s(t-\tau)$ is the transmitted Direct-Sequence Spread-Spectrum (DSSS) signal, $s(t)$, delayed by τ . The received signal, $r(t)$, is the convolution of the entire system impulse response, $h_0(t)$ (represented as "scale-delay-distort" model in the Figure 1), with the DSSS input signal,

$$r(t) = s(t) * h_0(t) \quad (2)$$

combining the above two equations gives,

$$R_{sr}(\tau) = h_c(t) * \{s(t-\tau) [s(t) * h_0(t)]\} \quad (3)$$

more specifically,

$$R_{sr}(\tau) = A_1 h_c(t) * \{s(t-\tau) [s(t-t_1) * h_1(t)]\} \quad (4)$$

which is the most general noiseless governing equation for describing the correlation function of the DSSSUE system.

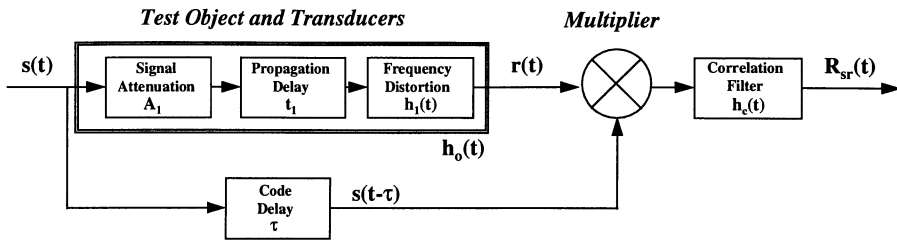


Figure 1. Signal processing model for the DSSSUE system.

GENERAL SYSTEM IMPLEMENTATION

Figure 2 depicts block diagram of a general implementation of the DSSSUE system [4?]. A binary spread-spectrum code, $c(t)$, is generated by the spread-spectrum code generator, which modulates a carrier, f_0 , through a spread-spectrum modulator. This translates the baseband signal, to a bandpass DSSS signal, $s(t)$, with center frequency, f_0 . The signal $s(t)$ is amplified by a power amplifier and fed to an ultrasonic transducer which transmits the ultrasonic DSSS signal into the test object. The return signal is picked up by the receive transducer and is input to the correlation receiver. The delayed transmitted DSSS signal, $s(t-\tau)$, acts as the reference signal for the matched filter correlator. The output of the correlation receiver is the desired ultrasonic correlation signature, $R_{sr}(\tau)$. This correlation signature is stored in the central memory of the host computer for future reference and signal processing to extract useful information about the test object.

APPLICATION TO INSPECTIONS

The performance of the DSSSUE technique have been verified through various experiments on laboratory test samples. These tests provided insight to the technical problems and limitations associated with both the implementations of the DSSSUE technique. The experience acquired in the laboratory testing will be applied to the tests conducted in the field. The results of some of these tests are presented below.

Cylindrical Steel Bar

This experiment was performed on three identical cylindrical steel bars of the form shown in Figure 3. Flaws in each bar were simulated as a circular groove of width 0.020 inch around the center with various incremental depths, listed in Table 1.

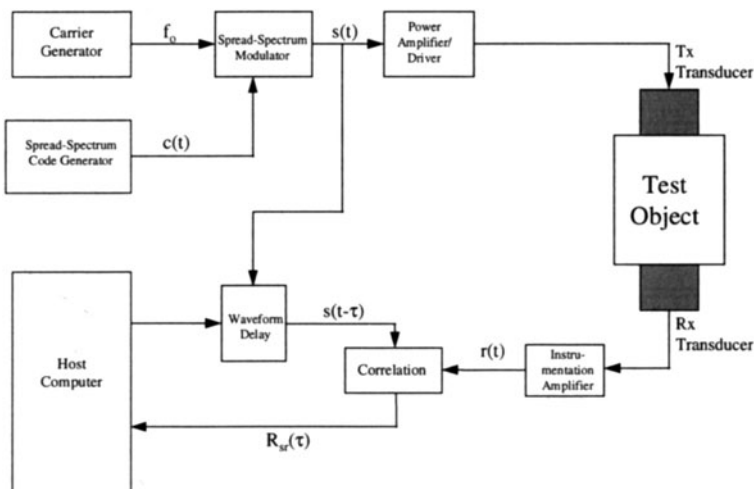


Figure 2. General implementation of the DSSSUE system.

Table-1: Steel bar test flaw depths.

	Baseline	Flaw 1	Flaw 2
BAR 1	0.0125	0.1	0.2
BAR 2	(none)	0.0125	0.025
BAR 3	0.025	0.05	0.1

all dimensions in inches.

Registration marks were milled into the test specimens at each end to avoid the effect of transducer registration on the correlation signatures. Multiple sets of data was taken at each step of the experiment, i.e. at the baseline and after introduction of each incremental flaw. A 11-bit shift register code with 5 MHz carrier and 2.5 MHz code chipping rate was used [2,5,8].

Results & Observations: Figure 4 shows a typical baseline correlation signature from bar-3. It was observed that there is a significant change in the correlation signature even with the introduction of a flaw as small as 0.0125 inch depth in a bar. Moreover, the introduction of new flaws add new correlation peaks in the ultrasonic signature which grow as the size of the flaw increases, as depicted in Figure 5. The amplitude of the correlation peaks is proportional to the size of the flaw and is consistent in the correlation signatures from each bar. Note that the position of the introduced flaw in the correlation signature can be predicted approximately by the travel time of the ultrasonic signal, which is possible only because of the simple geometry of the test object in this test.

This experiment verified the effect of transducer registration on the correlation signature. Although registration marks were made into the bars, the small changes in the registration due to change in the couplant between the transducer and the test object affected the differential experiment.

Water Drop Test

This test demonstrates the sensitivity of the DSSSUE system to a very small change in a test object. Figure 6 shows the test sample, it is a piece of copper with two holes. The intended small changes are introduced by varying the amount of water in the holes. The transducers are permanently mounted on the test object to maintain the same transducer registration between measurements. The 5 MHz broadband transducers and a 13-bit maximal length code was used.

The data was collected in three steps. For the baseline data set, the two holes in the standard test object were half filled with water and the cross-correlation obtained was used as the reference signature. Then, two more sets of data were collected after adding one drop and three drops of water to the baseline test setup of the test sample, respectively. Multiple sets of data was recorded at each step to confirm the repeatability of the test.

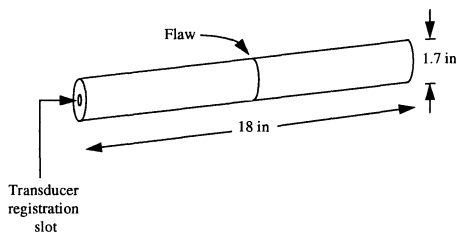


Figure 3. Test specimen for the cylindrical steel bar experiment.

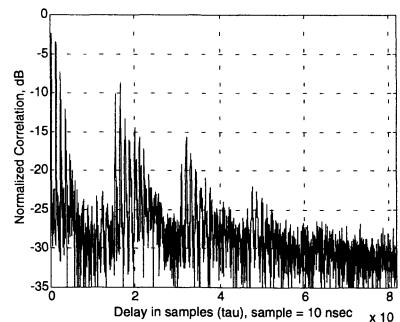


Figure 4. Baseline correlation signature from bar-3, flaw of 0.025 inch depth.

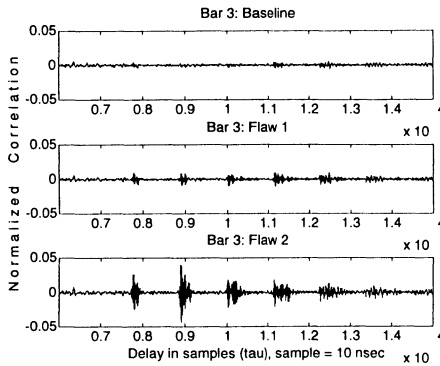


Figure 5. A portion of correlation signature from bar-3 showing growth of flaw correlation peaks with incremental flaws.

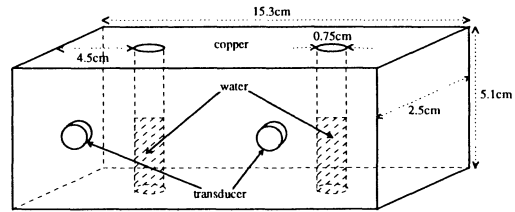


Figure 6. Test specimen for the water drop test.

Results & Observations: Figure 7 shows the baseline cross-correlation signature. It was observed that correlation function with the addition of water shows considerable difference from the baseline signatures. Moreover, the change in correlation signature with three drop of water shows greater deviation from the baseline signature than the one obtained after one water drop. Figure 8 shows the plots of simple differences between two baseline, between the baseline and one water drop signature and between the baseline and three drops signature, which correspond to no change, change of one drop and change of three drops of water. This shows that the DSSSUE system is capable of detecting a change as small as a drop of water.

Aluminum Bridge Girder

The DSSSUE technique can be applied equally effectively to the large dimension test specimens as to the small test objects [6?]. A differential experiment was performed on a girder from a highway bridge to prove this point. The test was carried out in the laboratory on the Aluminum I-beam bridge girder of the form shown in Figure 9. A 100 kHz carrier signal was used in this test, with an 11 bit shift register PN code.

In order to simulate the change in the test object, two identical blocks of steel of size $5'' \times 2.5'' \times 0.5''$ were used. These blocks were placed in different orientations on top of the beam 6 feet away from one of its ends to simulate various flaws, as shown in Figure 9. The transducers were clamped to the two ends of the top plate of the I-beam and the registration of the transducers was not disturbed during the experiment. Data was acquired under the setup conditions listed in Table-2.

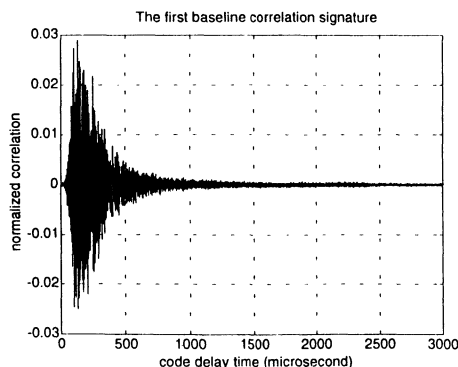


Figure 7. A baseline correlation signature from the water drop test.

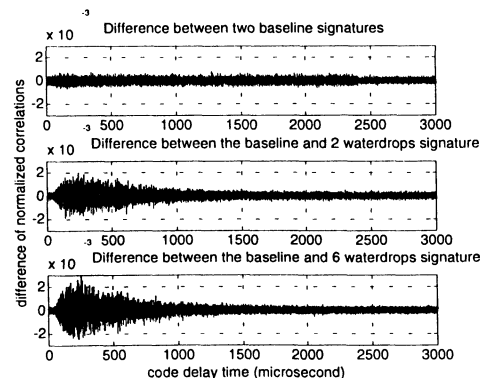


Figure 8. Change in the correlation difference with addition of 1 drop water.

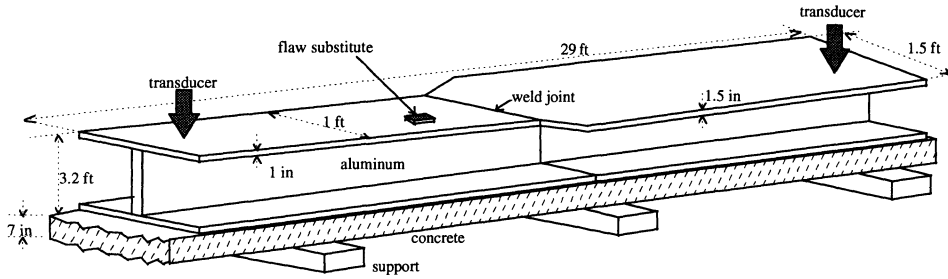


Figure 9. Test specimen for the Aluminum bridge girder experiment.

Table-2. Bridge girder experiment conditions.

datum	setup	contact area
Baseline	Aluminum Bridge girder (no flaw)	-----
Flaw-1	One block laying flat on the girder	12.5 sq in
Flaw-2	One block standing on its longer side	1.25 sq in
Flaw-3	Both blocks standing on their longer sides	2.5 sq in
Flaw-4	Both block laying flat on the girder	25 sq in

Correlation Signature Analysis: The first correlation from the baseline setup, R_{ref} , was selected as the reference signal and its difference from all the correlation signatures (both baseline and flaw setups) was computed. Thus,

$$\text{Correlation difference signature: } CDS_i = R_{ref} - R_i$$

where R_{ref} is the i-th correlation signature. A new measure for signature analysis was defined as the correlation difference energy (CDE), such that

$$CDE_i = \sum_N (CDS_i)^2 \quad (5)$$

where N is the total number of samples in the correlation signature.

Results & Observations: As expected, there was no observable change in the correlation signature with the introduction of the small simulated flaws. Therefore, CDE was computed. The histogram distribution of the CDE is plotted in Figure 10, which shows that CDE is an efficient measure of detecting and classifying small changes in the test object. Each simulated flaw in the test represents the acoustic inhomogeneity of a fatigue crack of different size. The position of each flaw CDE in the histogram is consistent with the size of the simulated flaw. A strong signal was observed because of the inherent low attenuation of Aluminum. Moreover, it was found that transducer placement is not critical in this test and similar results were obtained when the position of the ultrasonic transducers was changed.

Steel Piston Experiment (Industrial piece part)

DSSSUE technique is also ideally suited to the inspection and quality control of various piece parts in an assembly line environment. In order to verify the effectiveness of DSSSUE technique for such type of NDE requirements, the following experiment was performed on a steel piston of length 2.10 inches and diameter 0.63 inches.

Since the test object (piston) had no flat surface, cylindrical interface blocks were machined to attach the transmit and receive transducers to the test object. Transducer regis-

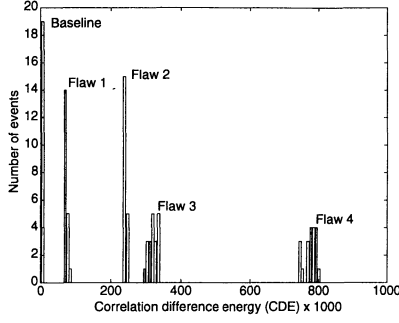


Figure 10. Distribution of the correlation difference energy for the test on the Aluminum bridge girder.

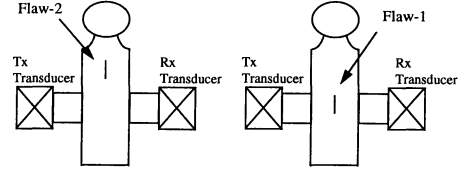


Figure 11. Simulated flaw positions in steel piston experiment.

tration was kept unchanged throughout the experiment. Flaw was simulated by attaching a small piece of magnetized steel wire on the outer surface of the piston. The experiment was performed for two locations of flaw, referred as flaw-1 and flaw-2; as shown in Figure 11. Three sets of data were recorded. First set corresponds to no flaw case, the second and third sets correspond to flaw-1 and flaw-2, respectively. The cross-correlation signatures were computed and the first no-flaw (baseline) signature used as the reference signal for the analysis of the correlation signatures.

Correlation Signature Analysis: In order to develop a criteria for the quantitative analysis of the correlation signatures and to distinguish between the "good" parts and the "bad" parts, two test statistics were defined. They are termed as SUF-1 and SUF-2 (spread-spectrum ultrasonic evaluation factor 1 & 2). SUF-1 is a measure of the degree of agreement between the reference signature and the unknown signature and is defined as:

$$(SUF-1)_i = \sum_n (R_{ref}(n) \cdot R_i(n)) \left(\sum_n (R_{ref}(n) \cdot R_{ref}(n)) \right)^{-1} \quad (6)$$

where R_{ref} is the baseline reference correlation signature. SUF-2 is a measure of the degree of agreement between the magnitudes of the Fourier transforms of reference the unknown signatures. Mathematically it is defined as:

$$(SUF-2)_i = \sum_n \text{fft}(R_{ref}(n)) \cdot \text{fft}(R_i(n)) \left(\sum_n [\text{fft}(R_{ref}(n))]^2 \right)^{-1} \quad (7)$$

Both SUF-1 and SUF-2 have a maximum value of 1, which corresponds to a perfect agreement. SUF-1 uses the phase information but can have sampling mismatch [1,4?] effect, where, SUF-2 loses the phase information but is independent of the sampling mismatch effect. The interval

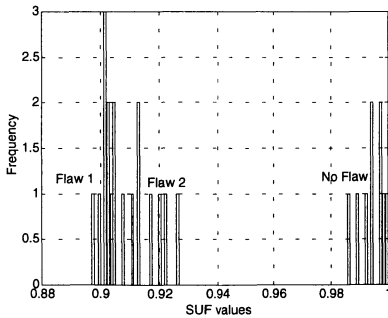


Figure 12. Histogram of SUF-1 for the small piston experiment.

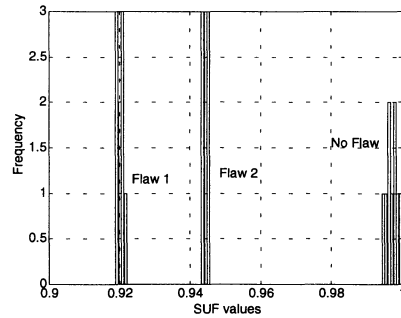


Figure 13. Histogram of SUF-2 for the small piston experiment.

of summation for the calculation of these parameters can vary in length and position in the correlation signature.

Results & Observations: The comparison of the SUF-1 and SUF-2 results for the experiment is show in Table 3 and histogram plots of Figure 12 and Figure 13.

Table-3. Comparison of SUFs for steel piston experiment.

	SUF-1	SUF-2
$\mu_{no\ flaw}$	0.9943	0.9973
$\mu_{flaw\ 1}$	0.9011	0.9212
$\mu_{flaw\ 2}$	0.9149	0.9443
$\sigma_{no\ flaw}$	0.0046	0.0016
$\sigma_{flaw\ 1}$	0.0024	0.0010
$\sigma_{flaw\ 2}$	0.0070	0.0006

μ is mean, σ is standard deviation.

This test further verified that the DSSSUE instrument can successfully identify parts with no flaw from parts with a simulated flaw. The relative performance of SUF-1 and SUF-2 was not obvious in this experiment as the two performed equally well in this case.

LESSONS LEARNED

An essential aspect of the development of the DSSSUE instrument is to compare the practical results with theory. This has also been a strong element in the experimental verification of the technique, the test results comply closely to the theoretical analysis and the limitations faced in the sensitivity and detectability make good theoretical and intuitive sense.

The most important lesson learned in the concept validation of the DSSSUE system is the importance of transducer registration, specially in the case of a differential experiment. A difference in the registration from one interrogation to another can limit our observability by masking small changes in the acoustic properties in the test object. For example, if CDE is used as correlation signature analysis, this would correspond to a spread in the histogram distribution which is proportional to the error in the transducer registration.

Various approaches were used for flaw detection and correlation signature study in the above experiments. SUF-1, SUF-2 and CDE proved to be valuable measures for classifying the flaw correlation signatures from the baseline signatures, though they do not provide a qualitative measure to distinguish one type of flaw from another. Moreover, they are independent of the sampling mismatch and other factors that restrict our observability in an differential experiment. However, it is required that a more sophisticated measured should be designed for correlation signature analysis.

Depending upon the geometry, propagation mode, material anisotropy of the test object, there may be an optimal DSSS signal center frequency. However, unless we want to fabricate custom transducers, commercial transducers may compromise optimal performance. Generally, large structures require DSSS signal with lower frequency modulating carrier. The signal modes supported a particular object can be found by interrogating it with a sweeping frequency signal and observing the SNR of received signal before selecting the DSSSUE test signal parameters.

The length of the PN code selected depends upon the required level of flaw observability, cost of equipment (memory) and processing time allowed for correlation. The sensitivity of the system increases as the length of the code sequence is increased but there is a trade off between the correlation output SNR and the processing time. Thus in applications that demand fast decision capability (such as an assembly line of a factory), shorter codes will be used and vice versa.

SUMMARY AND CONCLUSIONS

The tests performed in the laboratory environment conclusively verified the potential of the DSSSUE technique in nondestructive testing of materials. The test objects ranged from an object as small as the steel piston industrial part to the ones as large as the Aluminum bridge I-beam. These experiments point out technical limitations, but show that the sensitivity to change measured by DSSSUE provides new inspection technology.

One primary area of consideration in DSSSUE technology is the interpretation of the information contained in the ultrasonic correlation signature. The governing equations indicate that all information about the object under test is preserved by the correlation signature. However, its analysis is highly application dependent. In some cases (for example cylindrical steel bars test), the flaw information is available by simple inspection of the signature. In more complex situations, some simple techniques (SUF-1, SUF-2, CDE) based on detection theory in communications have been used successfully to quantitatively classify one flaw from another. In the future versions of the instrument, some form of artificial neural networks and artificial intelligence (AI) may be associated which will be capable of distinguishing different types of flaws, this research is in its premature shape at this time.

Transducer registration is critical for arbitrary sensitivity. For applications like bridge monitoring, it can be feasible to permanently mount the transducers on the structure to solve the problem, but in application such as quality control in a factory production line, the change in the correlation signature due to an error in the transducer registration needs to be resolved by ensuring consistent registration or by further understanding of registration effects.

In conclusion, it has been shown that DSSSUE instrument is capable of detecting microstructural flaws and other physical changes effecting its acoustic state. This technique is under development and it is anticipated that it will provide new inspection capabilities.

ACKNOWLEDGMENTS

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